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14. ABSTRACT

During the program, we pursued parallel and synergistic investigations focused on the development of energy—based models for high performance smart material transducers and model based control designs for these transducers to provide a robust control framework for actuators operating in highly nonlinear and hysteretic regimes.

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Model-Based Compensator and Control Design for High Performance Nonlinear Transducers

AFOSR F49620-01-1-0107

Final Report
for the period
January 1, 2001 - March 31, 2004

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Objectives

This research program focused on the development of energy-based models and model-based control designs for high performance smart material transducers comprised of piezoceramic, magnetostrictive and shape memory compounds. The first component of the program addressed the development of dynamic models which quantify the constitutive nonlinearities, hysteresis, frequency effects and thermal dependency of the materials. The second component focused on the development of linear and nonlinear control designs which utilize full and partial inverse compensators derived from the constitutive models. One objective was to employ these model-based control designs to construct smart actuators which have the full stroke and force capabilities of the nonlinear constituent smart materials but exhibit linear behavior throughout their drive range. A second objective was to achieve stringent control objectives, including micron-level tracking and broadband response capabilities, while operating in highly nonlinear and hysteretic regimes.

Status of Effort

During the program, we pursued parallel and synergistic investigations focused on the development of energy-based models for high performance smart material transducers and model-based control designs for these transducers to provide a robust control framework for actuators operating in highly nonlinear and hysteretic regimes. Through the development of a multiscale modeling approach comprised of energy relations at the lattice level and stochastic homogenization techniques to provide macroscopic constitutive relations, we have developed a unified framework for quantifying the hysteresis inherent to piezoceramic, magnetostrictive and shape memory compounds. These unified models are subsequently employed to construct approximate inverse relations which are incorporated in robust control designs for actuators employing these compounds. It has been illustrated through both numerical and experimental examples that the resulting control formulations facilitate high speed transduction while maintaining micron-level tracking tolerances. in the presence of sensor noise and disturbances accrued when approximating the nonlinear inverse maps.

Accomplishments

High performance transducers utilizing piezoelectric (PZT), magnetostrictive and shape memory alloy (SMA) components provide unprecedented control capabilities in a number of aerospace and aeronautic applications. Piezoelectric compounds are lightweight, provide both sensor and actuator capabilities, and operate effectively over a broad frequency range. Due to these attributes, they are presently being considered for shape morphing, vibration isolation, synthetic jet design and flow control. Magnetostrictive materials and films provide large force capabilities which are under present investigation for broadband blade morphing. Shape memory alloys achieve the highest output work density ratings of the considered materials and are being considered for chevron design to decrease jet engine noise while increasing aerodynamic efficiency. They also exhibit great potential for low frequency, high strain and force shape modification for vibration isolation and flow control. However, all of these materials also exhibit significant hysteresis and constitutive nonlinearities, as illustrated in Figure 1, which must be incorporated in models and accommodated in control designs to achieve the unique design capabilities which they provide for Air Force applications.

Development of a Unified Modeling Framework

At the beginning of the program, five fundamental model criteria were identified as necessary to achieve the flexibility and accuracy required for control design in high performance aerospace, aeronautic and industrial applications utilizing piezoceramic, magnetostrictive or shape memory
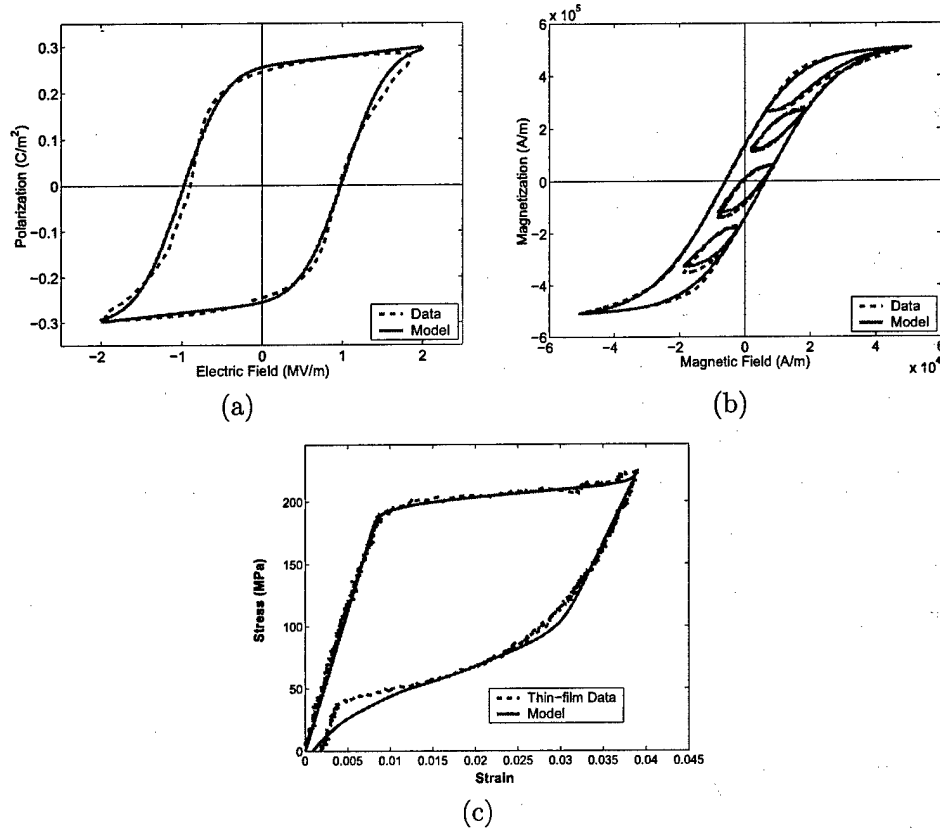
Figure 1: (a) Model comparison to quasistatic PZT5A data from [39], (b) model fit to Terfenol-D data from [37], and (c) model fit to thin film SMA data from [15].

actuators: (i) utilize the ferroic nature of the materials to construct unified modeling techniques, (ii) enforce closure in the dynamic minor loop models, (iii) include frequency and relaxation dependencies, (iv) include temperature dependencies, and (v) be amenable to efficient inversion for linear control design. During the program, we have developed a unified modeling framework which accomplishes all five of these criteria.

In the first step of the model development, we construct unified Helmholtz and Gibbs energy relations ψ and G using both statistical mechanics and phenomenological principals. For regimes in which thermal relaxation mechanisms are negligible, the local polarization $\overline{P}$, magnetization $\overline{M}$ or strain $\overline{\varepsilon}$ behavior of homogeneous materials is quantified by the necessary condition

$$\overline{e} = \frac{\partial G}{\partial \varphi}.$$ (1)

Here $e = P, M$ or ε and $\varphi = E, H$ or σ denotes the conjugate electric field, magnetic field, or stress. To quantify thermally-induced creep, relaxation or reptation effects, the Gibbs energy and relative thermal energy kT/V are balanced through the Boltzmann relation

$$\mu(G) = Ce^{-GV/kT}$$ (2)

where μ denotes the probability of achieving an energy level G, k is Boltzmann's constant, T denotes the temperature, and V is a reference volume.
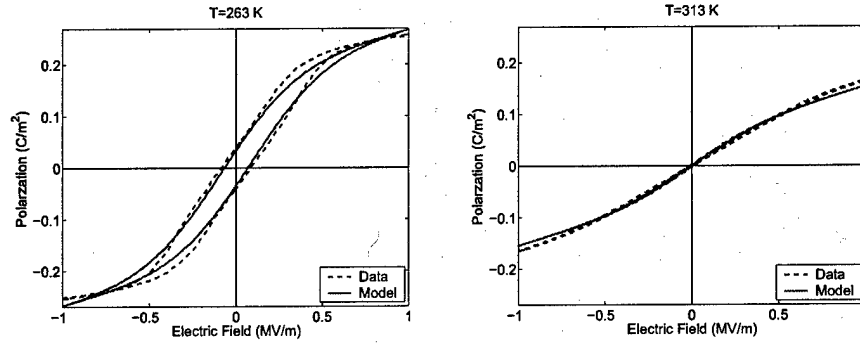
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Figure 2: Model predictions for electrostrictive PMN-PT-BT data at T=263 K and T=313 K.

To incorporate the effects of polycrystallinity, material nonhomogeneities, and variable effective fields, stochastic homogenization techniques are used to construct the general macroscopic models

$$[e(\varphi)](t) = \int_0^\infty \int_{-\infty}^\infty [\bar{e}(\varphi_e + \varphi; \varphi_c)](t)\nu_1(\varphi_e)\nu_2(\varphi_c)d\varphi_e d\varphi_c \tag{3}$$

where $\bar{e}$ is the kernel defined in (1) and ν_1 and ν_2 are densities that are estimated through least squares fits to data for a given material or transducer.

As detailed in [29, 36, 39] for PZT, [26] for magnetostrictive materials and [12, 14, 15] for shape memory films, the general model (3) enforces minor loop closure and provides a unified characterization framework for a broad range of ferroic compounds [37, 38]. Furthermore, it is illustrated in [1, 24, 26, 38, 39] that the framework accommodates certain temperature dependencies, relaxation mechanisms, and rate dependencies. Finally, it is amenable to inversion and use as a nonlinear inverse filter for linear control design [25, 35]. Hence it addresses criteria (i)-(v).

The performance of the model is illustrated for PZT, Terfenol-D, and shape memory films in Figure 1 to demonstrate its unified nature and capacity to guarantee biased minor loop closure in quasistatic operating regimes. The capability of the framework to characterize thermal and rate dependencies is illustrated in Figures 2 and 3 whereas properties of the inverse model are illustrated in Figure 4. Applications and additional compounds which employ this modeling framework are detailed in [2, 4, 5, 6, 8, 35].

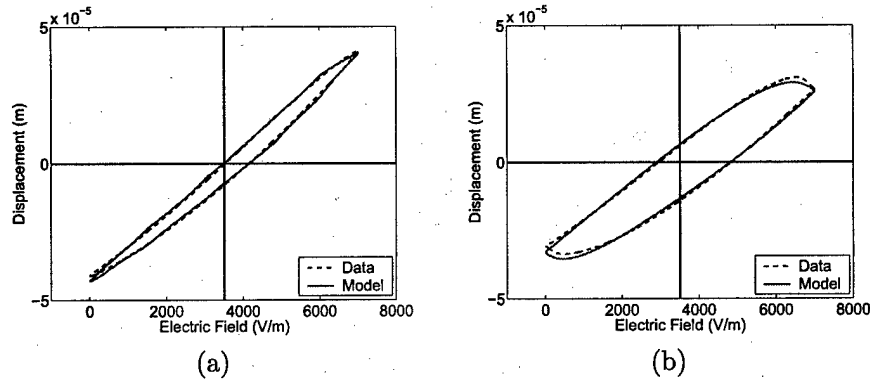(a)   (b)

Figure 3: Use of the polarization model to characterize the frequency-dependent behavior of stacked PZT actuators: (a) 0.28 Hz, and (b) 27.9 Hz.
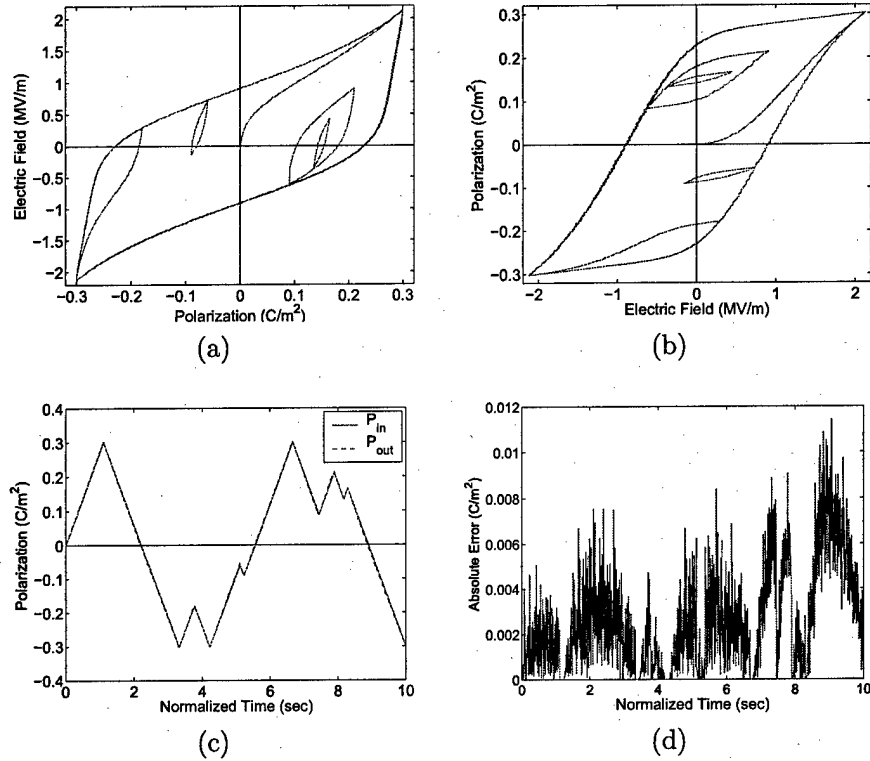
Figure 4: (a) Inverse relation P_{in}-E_{out}, and (b) forward relation E_{out}-P_{out}. (c) Comparison between P_{in} and P_{out}, and (d) absolute error $|P_{in} - P_{out}|$ for complete inversion process.

Control Design for Smart Transducers

The control component of the program has focused on the development of adaptive estimation techniques and optimal and robust control designs which achieve the high speed, high accuracy tracking criteria dictated by present aeronautic and aerospace applications utilizing smart material actuators operating in highly nonlinear and hysteretic regimes. To achieve these stringent criteria, control algorithms are designed to exploit the physics encapsulated in the unified models. This has led to the investigation of both linear [16]–[22] and nonlinear [41] control designs for PZT, magnetostrictive and SMA transducers.

To estimate parameters in the models, we have employed both offline least squares techniques and linear and nonlinear adaptive parameter estimation techniques [20]. The latter technique is motivated by the fact that smart transducers often exhibit temperature and pressure fluctuations which lead to temperature and stress-dependent parameters. Adaptive estimation techniques provide a mechanism for updating models that neglect these effects and fine-tuning models which incorporate these dependencies.

The investigation of robust control designs has focused on the use of the unified modeling framework to construct approximate inverse filters to partially compensate for hysteresis and constitutive nonlinearities in the manner depicted in Figures 4 and 5(a). This produces a disturbance d due to discretization errors which is significantly less than that due to uncompensated hysteresis in the absence of such filters. In addition to hysteresis disturbances, we consider both narrowband sensor noise s and broadband sensor disturbances n as illustrated in Figure 5(b). In the first facet of the investigation, we investigated the performance of $\mathcal{H}_2$ and $\mathcal{H}_\infty$ designs utilizing approximate inverse
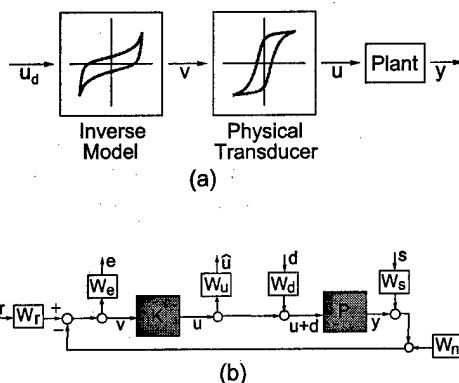
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Figure 5: (a) Inverse model employed as a filter in the hysteretic system. (b) Robust control configuration including inputs, disturbances and filters.

filters for high speed, high accuracy tracking. An important component of these designs focused on the construction of filters W_r, W_e, W_u, W_d, W_s and W_d to weight inputs and outputs.

As a prototype, we considered control design for magnetostrictive transducers which provide high force, broadband inputs but exhibit significant hysteresis. As a baseline, we considered the objective of obtaining a tracking accuracy of 1-2 micron at 3000 rpm. The numerical performance of an $\mathcal{H}_2$ design in the absence of an approximate inverse and utilizing such filters is illustrated in Figure 6. Details regarding the performance of the resulting $\mathcal{H}_2$ and $\mathcal{H}_\infty$ are provided in [16, 21, 22] where it is illustrated that inverse compensation is required to achieve the strict tracking criteria dictated by a number of present aerospace and aeronautic applications with high performance actuators operating in highly hysteretic regimes.

To experimentally validate the technique, we considered first the implementation of open loop designs both employing the inverse filters and devoid of filters. As illustrated in Figure 7 and [9], the incorporation and inversion of hysteresis mechanisms through model-based inverse filters yields open loop tracking capabilities that are up to tenfold more accurate than uncompensated designs. The experimental validation of these nonlinear model-based filters in feedback designs is under present investigation.
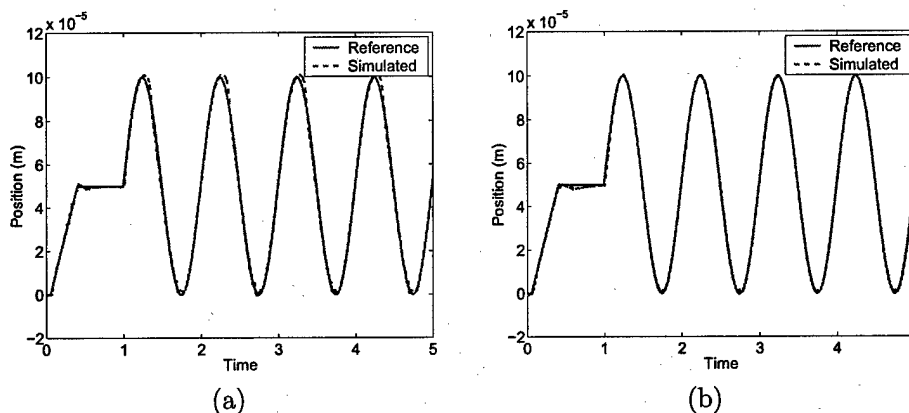

Figure 6: (a) Reference and simulated trajectory in the absence of an inverse filter (errors of 6-7 microns), and (b) using the approximate inverse filter depicted in Figure 4 and 5(a) (errors of 1-1.5 microns).
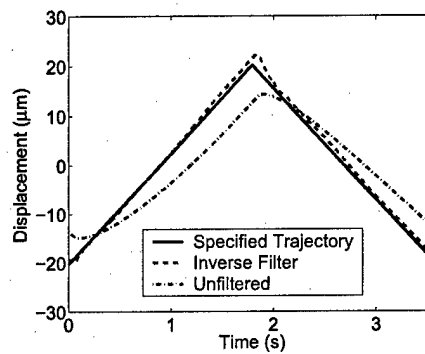
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Figure 7: Tracking performance in open loop experiments utilizing a model-based inverse and in the absence of a filter.

An additional facet focuses on nonlinear optimal control formulations which directly incorporate modeled physics through nonlinear state relations [41]. Solution of the resulting two-point boundary value problems yields open loop controls. Feedback is introduced by considering linear perturbations about the optimal trajectory. We are numerically testing the approach for high drive regimes and are designing experiments to test the real-time implementation of this perturbation control technique.

Personnel Supported

Brian Ball	Graduate Student, NCSU, Raleigh, NC
Emily Lada	Postdoc, NCSU, Raleigh, NC
James Nealis	Graduate Student, NCSU, Raleigh, NC
Ralph Smith	Professor, NCSU, Raleigh, NC

Interactions/Transitions

Conference, Colloquia and Workshop Presentations

- Department of Mathematics, Texas Tech University, Lubbock, TX, February 15, 2001 (Invited).

- SPIE's Eighth Annual Symposium on Smart Structures and Materials, Newport Beach, CA, March 5 and March 6, 2001.

- Department of Electrical Engineering, Iowa State University, April 13, 2001 (Invited).

- Workshop on Pluralism in Distributed Parameter Systems, University of Twente, The Netherlands, July 2-6, 2001 (Plenary).

- SIAM Conference on Control and Its Applications, San Diego, CA, July 14, 2001 (Plenary).

- 8th Conference on Control of Distributed Parameter Systems," Graz Austria, July 15-21, 2001 (Invited).

- 2001 ASME Design Engineering Technical Conferences, Pittsburgh, PA, September 10, 2001.

- Division of Applied Mathematics, Brown University, Providence, RI, September 28, 2001 (Invited).

- Department of Mathematics, Michigan State University, East Lansing, MI, November 8, 2001 (Invited).

- Fall Meeting of the Materials Research Society, Boston, MA, November 27, 2001.

- 38th IEEE Conference on Decision and Control, Orlando, FL, December 7, 2001.

- Department of Mechanical Engineering, Ohio State University, Columbus, OH, January 18, 2002 (Invited).

- Sandia National Laboratories, Albuquerque, NM, January 29, 2002 (Invited).

- SPIE's 9th Annual Symposium on Smart Structures and Materials, San Diego, CA, March 18, March 20, 2002.

- Electrical and Computer Engineering Department, UCSB, Santa Barbara, CA, March 22, 2002 (Invited).

- 2002 U.S. Navy Workshop on Acoustic Transduction Materials and Devices, Baltimore, MD, May 14, 2002.

- 14th US National Congress of Theoretical and Applied Mechanics, Blacksburg, VA, June 28, 2002 (Invited).

- Symposium in Honor of ICASE's 30th Anniversary, Newport News, VA, July 25, 2002 (Plenary).

- 2002 AFOSR Workshop on Dynamics and Control, Pasadena, CA, August 13, 2002 (Invited).

- Fifteenth International Symposium on Mathematical Theory of Networks and Systems, South Bend, IN, August 16, 2002 (Invited).

- Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, September 20, 2002 (Invited).

- Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC, September 26, 2002 (Invited).

- Symposium on New Trends in Nonlinear Dynamics and Control, and Their Applications, Naval Postgraduate School, Monterey, CA, October 19, 2002 (Invited).

- Department of Mathematics, Virginia Commonwealth University, Richmond, VA, November 18, 2002 (Invited).

- School of Computational Science and Information Technology, Florida State University, Tallahassee, FL, November 22, 2002 (Invited).

- 41st IEEE Conference on Decision and Control, Las Vegas, NV, December 13, 2002.

- SPIE's 10th Annual Symposium on Smart Structures and Materials, San Diego, CA, March 3, 2003.

- Department of Applied Mechanics & Engineering Sciences, University of California, San Diego, San Diego, CA, March 7, 2003 (Invited).

- 44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, Norfolk, VA, April 7, 2003.

- Acoustics and Fluid Mechanics Group, The Boeing Company, Seattle, WA, May 28, 2003 (Invited).

- 105th Annual Meeting and Exposition of the American Ceramic Society, Symposium on High Strain Piezoelectric Materials, Devices and Applications, Nashville, TN, May 30, 2003 (Invited).

- Fifth International Conference on Intelligent Materials, The Pennsylvania State University, State College, PA, June 15, 2003.

- Computational Control and Biological Systems VIII, Bozeman, MT, July 31, 2003 (Invited).

- 2003 AFOSR Workshop on Dynamics and Control, Destin, FL, September 9, 2003 (Invited).

- 42nd IEEE Conference on Decision and Control, Maui, HA, December 10, 2003 (Invited).

- Opening Workshop, SAMSI Program on Multiscale Model Development and Control Design, January 17, 2004 (Invited).

- Department of Mathematics, University of Wyoming, January 19, 2004 (Invited).

- School of Computational Science and Information Technology, Florida State University, March 10, 2004 (Invited).

- SPIE's 11th Annual Symposium on Smart Structures and Materials, San Diego, CA, March 15, March 16, 2004.

Transitions

1. *Curvature Enhanced Actuators – NASA LaRC:* The models and control designs developed for piezoceramic materials were employed in collaboration with scientists at ICASE and NASA Langley Research Center to quantify the displacements and forces generated by high performance THUNDER (THin layer UNimorph Driver and sEnsoR) actuators [2, 23, 40]. These actuators are being investigated for use as synthetic jets for active flow control, high speed valves for improved engine design, configurable shape modification of airfoils to improve flight characteristics, and shape modification in space structures such as configurable mirrors. Point of contact: Joycelyn Harrison, NASA Langley Research Center, Hampton, VA, 757-864-4239.

2. *Configurable Mirrors – AFRL, Kirtland AFB:* An investigation was initiated with scientists in the Space Vehicles Directorate at Kirtland AFB to investigate the feasibility of employing SMA compounds for configuration and vibration attenuation in membrane and articulated mirrors. Aspects of the investigation relied on models and control techniques developed under the AFOSR program. To initiate this investigation, Robertson and Smith mentored the project "Design of a Membrane Aperture Deployable Structure" at the Industrial Mathematics Modeling Workshop held at North Carolina State University on July 22-31, 2002 which resulted in the paper [7]. Point of contact: Lawrence "Robbie" Robertson, AFRL, Kirtland AFB, 505-846-7687.

3. *Nanopositioning – Asylum Research:* The models quantifying constitutive nonlinearities, hysteresis, thermal effects, and frequency effects in piezoceramic materials will be employed in conjunction with model-based control laws to improve the resolution and efficiency of nanopositioners including high speed scanning for atomic force microscopy. Point of contact: Jason Cleveland, Asylum Research, Santa Barbara, CA, 805-692-2800.

4. *SMA Thin Films and MEMs – Sandia:* Shape memory alloy models developed through AFOSR support are being investigated at Sandia National Laboratories for characterization and control design in applications employing shape memory films and MEMs. The potential benefit to the Air Force mission is significant since SMA films and MEMs retain the high strain properties of bulk SMA but have the potential for operating at significantly higher frequencies. Point of contact: James Redmond, Sandia National Laboratories, Albuquerque, NM, 505-844-3136.

5. *SMA Chevrons and Torque Tubes – Boeing:* The 1-D SMA models developed through the AFOSR program are being extended in collaboration with Boeing scientists to 2-D and 3-D geometries inherent to chevrons used to reduce jet noise and decrease drag with potential application to improved inlet channel design. Similar models are being considered by Boeing as optimization tools for the design of SMA torque tubes to change the camber of rotorcraft blades. In both cases, models and control designs will be validated using data from Boeing experiments and flight tests. Point of contact: James Mabe, Boeing Phantom Works, Seattle, WA, 206-655-0091.

6. *PZT Unimorphs – Boeing:* Nonlinear structural models developed through AFOSR support are being considered at Boeing for characterizing the hysteretic and nonlinear behavior of PZT-based unimorphs under investigation for flow control and improved flight capabilities. The second phase of the investigation will focus on model-based control design and implementation of the unimorphs. This can potentially impact a broad range of flow control problems of interest to the Air Force and Boeing. Point of contact: James Mabe, Boeing Phantom Works, Seattle, WA, 206-655-0091.

Awards

- Recipient of the *Iowa State University Foundation Award for Early Achievement in Research*, 1997.

- The paper "Nonlinear adaptive parameter estimation algorithms for hysteresis models of magnetostrictive actuators," [20], presented by James Nealis, was awarded the *3rd Place Best Student Paper Award 2002* at the SPIE Symposium on Smart Structures and Materials, March 2002.

- The paper "Analytical and Experimental Issues in Ni-Mn-Ga Transducers," [8], presented by LeAnn Faidley, was awarded the *2nd Place Best Student Paper Award 2003* at the SPIE Symposium on Smart Structures and Materials, March 2003.

Publications
Publications resulting from work supported by this grant are listed as references.

References

[1] B.L. Ball and R.C. Smith, "A stress-dependent hysteresis model for PZT-based transducers," CRSC Technical Report CRSC-TR04-14; Proceedings of the SPIE, Smart Structures and Materials 2004, to appear.

[2] B.L. Ball, R.C. Smith and Z. Ounaies, "A dynamic model for THUNDER transducers," Proceedings of the SPIE, Smart Structures and Materials 2003, Volume 5049, pp. 100-111, 2003.

[3] M.J. Dapino, R.C. Smith, F.T. Calkins and A.B. Flatau, "A magnetoelastic model for Villari-effect magnetostrictive sensors," *Journal of Intelligent Material Systems and Structures,* 13(11), pp. 737-748, 2002.

[4] G. Daspit, C. Martin, J-H. Pyo, C. Smith, H. To, K.M. Furati, Z. Ounaies and R.C. Smith, "Model Development for Piezoelectric Polymer Unimorphs," Proceedings of the SPIE, Vol. 4693, pp. 514-524, 2002.

[5] P.R. Downey, M.J. Dapino and R.C. Smith, "Analysis of hybrid PMN/Terfenol broadband transducers in mechanical series configuration," Proceedings of the SPIE, Smart Structures and Materials 2003, Volume 5049, pp. 168-179, 2003.

[6] B. Edmonds, Jr., J. Ernstberger, K. Ghosh, J. Malaugh, D. Nfodjo, W. Samyono, X. Xu, D. Dausch, S. Goodwin and R.C. Smith, "Electrostatic operation and curvature modeling for a MEMS flexible film actuator," CRSC Technical Report CRSC-TR04-8; Proceedings of the SPIE, Smart Structures and Materials 2004, to appear.

[7] J. Enders, S. Kas-Danouche, W. Liao, B. Rasmussen, T. Anh Vo, K. Yokley, L. Robertson and R.C. Smith, "Design of a membrane aperture deployable structure," Proceedings of the 44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, Norfolk, VA, AIAA-2003-1494, 2003.

[8] L.E. Faidley, M.J. Dapino, G.N. Washington, R.C. Smith and T.A. Lograsso, "Analytical and experimental issues in Ni-Mn-Ga transducers," Proceedings of the SPIE, Smart Structures and Materials 2003, Volume 5049, pp. 1-12, 2003.

[9] A.G. Hatch, R.C. Smith and T. De, "Model development and control design for broadband speed atomic force microscopy," Proceedings of the 43rd IEEE Conference on Decision and Control, 2004, to appear.

[10] A.G. Hatch, R.C. Smith and T. De, "Model development and control design for high speed atomic force microscopy," CRSC Technical Report CRSC-TR04-17; Proceedings of the SPIE, Smart Structures and Materials 2004, to appear.

[11] D.J. Kolepp and R.C. Smith, "Narrowband control design for smart structural systems," Proceedings of the 18th ASME Biennial Conference on Mechanical Vibration and Noise, 2001.

[12] J.E. Massad and R.C. Smith, "A domain wall model for SMA characterization," Proceedings of the SPIE, Smart Structures and Materials 2002, Volume 4693, pp. 324-335, 2002.

[13] J.E. Massad and R.C. Smith, "A domain wall model for hysteresis in ferroelastic materials," *Journal of Intelligent Material Systems and Structures,* 14(7), pp. 455-471, 2003.

[14] J.E. Massad and R.C. Smith, "A homogenized free energy model for hysteresis in thin-film shape memory alloys," *International Journal on the Science and Technology of Condensed Matter Films*, submitted.

[15] J.E. Massad, R.C. Smith and G.P. Carman, "A free energy model for thin-film shape memory alloys," Proceedings of the SPIE, Smart Structures and Materials 2003, Volume 5049, pp. 13-23, 2003.

[16] J.M. Nealis, *Model-Based Robust Control Designs for High Performance Magnetostrictive Transducers*, PhD Dissertation, North Carolina State University, May 2003.

[17] J. Nealis and R.C. Smith, "Partial inverse compensation techniques for linear control design in magnetostrictive transducers," Proceedings of the SPIE, Smart Structures and Materials 2001, Volume 4326, pp. 462-473, 2001.

[18] J.M. Nealis and R.C. Smith, "An Adaptive Control Method for Magnetostrictive Transducers with Hysteresis," Proceedings of the 40th IEEE Conference on Decision and Control, 2001.

[19] J.M. Nealis and R.C. Smith, "Robust control of a magnetostrictive actuator," Proceedings of the SPIE, Smart Structures and Materials 2003, Volume 5049, pp. 221-232, 2003.

[20] J.M. Nealis and R.C. Smith, "Nonlinear adaptive parameter estimation Algorithms for Hysteresis Models of Magnetostrictive Actuators," Proceedings of the SPIE, Vol. 4693, pp. 25-36, 2002.

[21] J.M. Nealis and R.C. Smith, "$\mathcal{H}_\infty$ control design for a magnetostrictive transducer," Proceedings of the 42nd IEEE Conference on Decision and Control, Maui, HA, pp. 1801-1806, 2003.

[22] J.M Nealis and R.C. Smith, "Model-based robust control design for magnetostrictive transducers operating in hysteretic and nonlinear regimes," CRSC Technical Report CRSC-TR03-25; *IEEE Transactions on Automatic Control*, submitted.

[23] Z. Ounaies, K. Mossi, R.C. Smith and J. Bernd, "Low-field and high-field characterization of THUNDER actuators," Proceedings of the SPIE, Smart Structures and Materials 2001.

[24] J.K. Raye and R.C. Smith, "A temperature-dependent hysteresis model for relaxor ferroelectric compounds," CRSC Technical Report CRSC-TR04-13; Proceedings of the SPIE, Smart Structures and Materials 2004, to appear.

[25] R.C. Smith, "Inverse compensation for hysteresis in magnetostrictive transducers," *Mathematical and Computer Modelling*, 33, pp. 285-298, 2001.

[26] R.C. Smith, M.J. Dapino and S. Seelecke, "A free energy model for Hysteresis in Magnetostrictive Transducers," *Journal of Applied Physics*, 93(1),pp. 458-466, 2003.

[27] R.C. Smith and A.G. Hatch, "Parameter estimation techniques for a polarization hysteresis model," CRSC Technical Report CRSC-TR04-19; Proceedings of the SPIE, Smart Structures and Materials 2004, to appear.

[28] R.C. Smith, A.G. Hatch and T. De, "Model development for piezoceramic nanopositioners," Proceedings of the 42nd IEEE Conference on Decision and Control, Maui, HA, pp. 2638-2643, 2003.

[29] R.C. Smith, A.G. Hatch, B. Mukherjee and S. Liu, "A homogenized energy model for hysteresis in ferroelectric materials: General density formulation," CRSC Technical Report CRSC-TR04-23; *Journal of Intelligent Material Systems and Structures*, submitted.

[30] R.C. Smith and H.L. Hom, "A temperature-dependent constitutive model for relaxor ferroelectrics," CRSC Technical Report CRSC-TR00-26; *Journal of Intelligent Material Systems and Structures*, to appear.

[31] R.C. Smith and J.E. Massad, "A unified methodology for modeling hysteresis in ferroic materials," Proceedings of the 2001 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol 6, Pt B, pp. 1389-1398, 2001.

[32] R.C. Smith and Z. Ounaies, "Model Development for High Performance Piezoelectric Polymers," MRS Symposium Proceedings Vol. 698, pp. 217-222, 2002.

[33] R.C. Smith and M. Salapaka, "Model development for the positioning mechanisms in an atomic force microscope," *International Series of Numerical Mathematics*, Vol 143, pp. 249-269, 2002.

[34] R.C. Smith, M.V. Salapaka and L. Cherveny, "A Preisach model for quantifying hysteresis in an atomic force microscope," Proceedings of the SPIE, Smart Structures and Materials 2002, Volume 4693, pp. 498-504, 2002.

[35] R.C. Smith, M.V. Salapaka, A. Hatch, J. Smith and T. De, "Model development and inverse compensator design for high speed nanopositioning," Proceedings of the 41st IEEE Conference on Decision and Control, Las Vegas, NV, 2002.

[36] R.C. Smith and S. Seelecke, "An energy formulation for Preisach models," Proceedings of the SPIE, Smart Structures and Materials 2002, Volume 4693, pp. 173-182, 2002.

[37] R.C. Smith, S. Seelecke, M.J. Dapino and Z. Ounaies, "A unified model for hysteresis in ferroic materials," Proceedings of the SPIE, Smart Structures and Materials 2003, Volume 5049, pp. 88-99, 2003.

[38] R.C. Smith, S. Seelecke, M.J. Dapino and Z. Ounaies, "A unified framework for modeling hysteresis in ferroic materials," CRSC Technical Report CRSC-TR03-26; *Journal of the Mechanics and Physics of Solids,* submitted.

[39] R.C. Smith, S. Seelecke, Z. Ounaies and J. Smith, "A free energy model for hysteresis in ferroelectric materials," *Journal of Intelligent Material Systems and Structures*, 14(11), pp. 719-739, 2003.

[40] R. Wieman, R.C. Smith, T. Kackley, Z. Ounaies and J. Bernd, "Displacement models for THUNDER actuators having general loads and boundary conditions," Proceedings of the SPIE, Smart Structures and Materials 2001, Volume 4326, pp. 252-263, 2001.

[41] J. Zhong, S. Seelecke, R.C. Smith and C. Büskens, Optimal control of piezoceramic actuators," Proceedings of the SPIE, Smart Structures and Materials 2003, Volume 5049, pp. 264-274, 2003.